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Geophysical Predictions: Sun-Weather

by

John M. Wilcox

Office of Naval Research
Contract N00014-76-C-0207

National Aeronautics and Space Administration
Grant NGR 05-020-559

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Grant ATM74-19007
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The present status of sun-weather research is summarized. Recommendations for future research are given.

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GEOPHYSICAL PREDICTIONS: SUN-WEATHER

by

John M. Wilcox
Institute for Plasma Research
Stanford University
Stanford, California 94305

I. Summary

Much of the flavor of sun-weather investigations at the present time is caught in an exchange that occurred at a meeting of the Royal Astronomical Society at Exeter in March 1975 (Royal Astronomical Society, 1975):

D.R. Davies: 'I am very sceptical of this Sun-weather business. One needs to be very careful in the interpretation of the sort of statistics used by King. It is no good saying there are correlations without suggesting realistic mechanisms.'

J.W. King: 'That is just the sort of reaction I have come to expect from some professional meteorologists. There is little doubt that the correlations are real. Even if meteorologists refuse to research possible mechanisms, geophysicists surely will.'

For well over one hundred years some geophysicists have been attempting to convince meteorologists that the changing sun may cause changes in our weather and climate. We must define what we mean by "changing sun". Everyone agrees that the almost-constant radiant energy at visible wave lengths drives the weather machine, and indeed is the ultimate energy source for almost all activities on earth. On the other hand, the possibility that changes in the sun may cause changes in weather and climate has been a controversial and sometimes emotional issue.

Several decades ago the "changing sun" in this context would have meant small changes in the radiant energy output of the sun (the so-called solar constant). Charles Greeley Abbot, the former secretary of the

Smithsonian Institution, devoted much of his life to this question. He lived to the age of 101 years, and a few months before his death in 1974 he addressed a Symposium on this subject at Goddard Space Flight Center.

Nowadays, we can consider some other aspects of the "changing sun" that may influence weather and climate. A solar wind flows out away from the sun in all directions, carrying with it the sun's magnetic field and taking about four days to reach the earth. Large solar flares can send shock waves out into the solar wind that reach the earth in one or two days. These shock waves, and also some quasi-stationary structures in the solar wind considerably influence the intensity at Earth of cosmic rays from the galaxy and of high energy protons and electrons from the sun.

The rotation period of the sun as seen from the earth is about 27 days. Observations show that at least in certain wave lengths, such as the ultraviolet, the intensity of the solar radiation received at earth varies with a 27-day period, corresponding to the presence of quasi-stationary large-scale structures on the sun. These solar structures are the source of similar structures in the solar wind which are known to influence several terrestrial effects, such as radio communication outages, power line outages, and high radiation levels at airplanes and spacecraft.

The subject of this chapter is the question of whether one (or perhaps several) of these aspects of the "changing sun" may influence weather and climate on Earth. The size of such an influence, if indeed one exists, could be anywhere from a real but very small influence whose practical importance might lie mainly in improving our understanding of meteorological processes, to a substantial influence that might have direct significance for forecasting. Much additional work will be needed to establish a firm answer to these questions.

II. The Scientific Problem

The principal scientific problem at the present time is to establish the reality, or lack thereof, of sun-weather influences. As the reality becomes more likely increasing numbers of scientists and increasing amounts of support are involved with the investigations.

A comprehensive description of observational and theoretical investigations is available in the Proceedings of a Symposium on "Possible Relationships Between Solar Activity and Meteorological Phenomena" held at Goddard Space Flight Center in November 1973 (Bandeen and Maran, 1975) and in two recent reviews by King (1975) and by Wilcox (1975). I will not attempt a further review of these reviews and symposium proceedings, but rather refer the interested reader to them for technical details. I will concentrate on a discussion of the reality of the sun-weather investigation with which I am most familiar, and will supplement this discussion with some recent results that became available after the reviews and proceedings were published.

A. Some Recent Work

I will first describe (excerpted from Wilcox, 1976) some recent work involving the cooperative efforts of several scientists at several institutions. For a decade or more W.O. Roberts at the National Center for Atmospheric Research and the University of Colorado in Boulder has been a leading American worker on the subject of sun-weather interactions. Some recent work by Roberts and Olson (1973a,b) studied days on which geomagnetic activity had a sizeable increase, which was assumed to have a solar cause. They also studied the history of low-pressure troughs (cyclones) from the Gulf of Alaska as they moved across the continental United States, and found the troughs associated with geomagnetic activity were significantly larger on the average than troughs associated with intervals of quiet geomagnetic conditions. The vorticity area index, a measure of the size of low-pressure troughs devised by Roberts and Olson, has been used in several subsequent investigations.

A low-pressure trough is a large rotary wind system, having a diameter of a few thousand kilometers, that is usually associated with clouds, rain, or snow. Although the formation and structure of low-pressure troughs have been studied in some detail, it is not possible in general to predict the time and place at which a trough will form. This is one reason why the skill in short-range weather prediction becomes small (that is, little better than a prediction of average properties) within two or three days (Leith, 1975). The vorticity area index devised by Roberts and Olson can be computed from maps of the height of constant-pressure (300-mbar) surfaces by using the geostrophic wind approximation. These maps are prepared twice a day, at 0 and at 12 universal time (U.T.), by the National Weather Service. The circulation of the air mass in a trough is defined as the line integral of the velocity of the air around a closed path. Vorticity is defined as the circulation per unit area. In our use of the vorticity area index, it is computed for the portion of the Northern Hemisphere north of 20^{o}N. The index is now defined as the sum of all areas in which the vorticity exceeds a certain threshold, which is chosen so that all well-formed troughs are included. Once the threshold level ($20 \times 10^{-5} sec^{-1}$ in our work) has been chosen, the computation of the vorticity area index is completely objective.

The results of the investigations to be described in this chapter will be presented in terms of graphs in which the meteorological input to the investigation is plotted on the ordinate and the solar input is plotted on the abscissa. The meteorological input is the vorticity area index just described. Now we must consider what the solar input will be.

Roberts and Olson (1973a, b) assumed that the increase in geomagnetic activity used in their analysis were caused by the changing sun. This assumption was challenged by Hines (1973), who suggested that some geomagnetic activity may be caused by current systems induced by motions of the lower atmosphere. To the extent that this assumption is correct, the assumed chain "sun → geomagnetic increase → weather change" would be replaced by a "weather change → geomagnetic activity → weather change". In my opinion such an influence on the investigations of Roberts and Olson (1973a, b) can

probably be neglected. Nevertheless, it is clearly an advantage in this situation if a structure that is clearly of solar origin can be used for the solar input in the investigation.

For this purpose we consider the solar sector structure, which is a fundamental large-scale property of the sun. A description of several solar, interplanetary, and terrestrial properties of this structure is available (Wilcox, 1968). The structure is readily perceived in observations by spacecraft magnetometers of the interplanetary magnetic field that is swept past the earth by the solar wind. For several consecutive days this interplanetary field will be observed to have a polarity directed away from the sun. For the next several days it will be observed to have a polarity directed toward the sun. These two sectors are separated by a thin boundary that typically is swept past the earth during an interval measured in tens of minutes.

In the investigations described here, the time at which a sector boundary is observed to sweep past the earth is used as a zero phase reference. This sharply defined time is very convenient for the analysis, but it must be emphasized that the sector boundary itself is probably not an important influence on the weather. Furthermore, the large-scale sector pattern of the interplanetary magnetic field (and associated structures in the solar wind) is not necessarily a physical influence on the weather. The solar influence (if there is one) described in this chapter could be related to variations in the solar ultraviolet emission in the solar "constant", in some manifestation of the changing solar magnetic field such as energetic particle emission, in an influence of the extended solar magnetic field on galactic cosmic rays incident at the earth, or in some other unknown factor. In any event, the extended solar sector structure as observed with spacecraft in the interplanetary magnetic field near the earth is clearly a solar structure that is not influenced by terrestrial weather. We now consider further the possibility that some aspect of the solar structure may influence the weather.

B. Extension of Earlier Investigations

Our group at Stanford joined forces with Roberts and Olson to extend their original investigations. The first results (Wilcox et al., 1973, 1974) of this collaboration are shown in Figure 1, where the average change in the vorticity area index is plotted against days from sector boundary as the sector structure is swept past the earth by the solar wind. Day zero represents the time at which a sector boundary passed the earth. We see in Figure 1 that on the average the vorticity area index reaches a minimum approximately one day after the boundary passage. The amplitude of the effect from the minimum to the adjacent maximum is about 10 percent. When we consider that weather usually consists of relatively small changes about climate (the average properties), this represents a sizeable and important change. I repeat the warning that the sector boundary passage, although very convenient as a precise timing mark, almost surely does not have an important physical influence on the weather. The large-scale sector in the interplanetary magnetic field also may not have a direct causal influence on the weather, but may merely delineate some solar structure that does. Figure 1 is computed for 300 mbar, but similar results are found for 200, 500, and 700 mbar.

The result shown in Figure 1 is prominent only during the winter months (Wilcox et al., 1975). This may be related to the fact that this is the season in which the equator-to-pole temperature difference are the largest, producing the largest stresses on the earth's atmospheric circulation.

C. Significance and Reality of the Results

The original work shown in Figure 1 used 54 sector boundary crossing times observed with spacecraft orbiting the earth. The evidence for the significance and reality of the claimed effect rested on the size of the standard error of the mean (the error bar shown in Figure 1) and on the result shown in Figure 2 that the effect persisted when the list of boundaries used in Figure 1 was divided into two parts according to (a) the magnetic polarity change at the boundary, (b) the first or last half of the winter, and (c) the yearly intervals 1964 to 1966 and 1967 to 1970.

There has been some discussion of the appropriate way to compute the error bar in Figure 1. We feel that the correct method was used, but in any case we describe some independent tests of reality.

A further test of significance is to inquire if the effect persists in new observations (Wilcox et al., 1976). Figure 3a shows our original analysis, while Figure 3b shows the same analysis performed with a list of 81 new boundary passage times, none of which are included in the analysis of Figure 3a. The new boundary passage times used in Figure 3b were obtained by increasing the interval examined to 1963 to 1973, and by supplementing spacecraft observations of the interplanetary magnetic field polarity with inferred polarities of the interplanetary field obtained from analysis of polar geomagnetic variations (Svalgaard 1972, 1973, 1975; Wilcox 1972).

The most important test of the significance of the results claimed in Figure 1 was made by Hines and Halevy (1975), who stated, "Reports of short-term Sun-weather correlations have been greeted with skepticism by many". They subjected the data used in preparing Figure 1 to a variety of statistical tests and requested the analysis of new data shown in Figure 3. They concluded that "We find ourselves obliged, however, to accept the validity of the claim by Wilcox et al., and to seek a physical explanation".

What does one conclude from all of the above? The results of the past century suggest that a certain caution would be very appropriate. The one statement that I would make with complete conviction is that this appears to be an interesting subject that should be vigorously pursued.

III. Societal Concerns, Need for Predictions and Prospects for Improvement

An understanding of the physical mechanism(s) of an influence of the changing sun on weather could well yield an improvement in the forecasting of climate, to the extent that the factors influencing climate represent longer-term averages of the transient factors influencing weather. We may come first to an understanding of the factors influencing weather since in a given interval, say ten years, there are many more repetitions of weather changes than of climate changes.

The needs of society for improved forecasting of weather and of climate are obvious and do not need to be examined in detail here. The suffering and deaths caused by recent droughts in the Sahel and the large international purchases of wheat following crop failures in the Soviet Union are recent examples.

We cannot quantify possible societal benefits from the understanding of sun-weather effects until we are sure that such effects exist and we understand the magnitude of the effects. If sun-weather effects turn out to be real but of very small magnitude, the resulting increase in our understanding of meteorological processes may still improve forecasting of weather and climate with the resulting societal benefits. If sun-weather effects should turn out to have a significant magnitude then they may become a direct part of such forecasting.

A. Comparison of Sun ⟶ Weather and Sun ⟶ Geomagnetic Activity

In trying to assess the status of sun-weather investigations at the present time it is useful to compare with investigations of the influence of the changing sun on geomagnetic activity, i.e. changes in the earth's magnetic field on a time scale of tens of minutes. For about 100 years some geophysicists have been claiming that variations in the earth's magnetic field are caused by the changing sun. In the early years this viewpoint was quite controversial. In his famous Presidential Address in 1892 to the Royal Society, Lord Kelvin had some firm comments for such geophysicists. He considered the amount of energy involved in geomagnetic activity and concluded "This result, it seems to me, is absolutely conclusive against the supposition that terrestrial magnetic storms are due to magnetic action of the sun; or to any kind of dynamical action taking place within the sun, or in connection with hurricanes in his atmosphere, or anywhere near the sun outside." (Kelvin, 1892). In spite of these strictures some geophysicists and astronomers proceeded with their investigations, and today it is universally accepted that the changing sun is the cause of many variations in the earth's magnetic field.

B. Evaluation of Sun $\longrightarrow$ Weather at the Present Time

What are the prospects for improvement of our understanding of the sun-weather situation in comparison to this description of the sun-geomagnetic activity situation? Sun-weather investigations are at an early point on the time scale of sun-geomagnetic activity investigations, perhaps not long after Lord Kelvin admonished the geophysicists and astronomers. Does this then mean that we will have to wait for 75 years until we can give a fairly complete and concise summary of the physical conditions related to sun-weather? Almost surely not, because spacecraft and modern observational and computational tools have given us a much more powerful handle on the problem.

The meteorological system is much more complex than the geomagnetic field. In meteorology we have to deal with many complex internal processes and with exchanges of energy with large reservoirs such as the oceans. If this complexity of the meteorological system prevents or at least delays an understanding comparable to what we now have of the simpler geomagnetic field, it may still be possible to utilize correlations between the changing sun and meteorological phenomena on an empirical basis, if such correlations can be shown to be real and of sufficient magnitude. Of course an understanding of the basic physical processes would be much more satisfying from both the practical and the intellectual viewpoints.

A further important point to consider in the analogy between sun-geomagnetic activity and sun-weather investigations is the quantitative way in which the terrestrial system (the geomagnetic field or meteorological processes) is described. The concise description of geomagnetic activity became possible only when the classical and widely used index of geomagnetic activity (Bartel's index Kp) was set aside and a newer and more descriptive index (Mayaud's index am) was used. There is no way in which this concise description could have been obtained using the older index. Similarly, it is not at all clear that present investigations of sun-weather effects have used an optimum quantitative description of meteorological processes. Indeed, it is very likely that they have not. The search for the optimum quantitative description of meteorological processes is one of the most important parts of future sun-weather investigations. Here we can take heart in the improved possibilities offered by spacecraft and by modern observational and computational techniques.

An important element in the prospects for improvement of sun-weather investigations is the increasing number of scientists who have become interested in this subject. This is both a cause and a result of several recent symposia and organizational activities. A landmark was the symposium on "Possible Relationships Between Solar Activity and Meteorological Phenomena" held at Goddard Space Flight Center in November 1973 (Bandeen and Maran, 1975). A joint meeting on this subject was held by the American Meteorological Society and the Solar Physics Division of the American Astronomical Society in January 1975 in Denver. A workshop "The Solar Constant and the Earth's Atmosphere" was held at Big Bear Solar Observatory in May 1975 (Zirin and Walter, 1975). A symposium on the subject was held at the General Assembly of the International Union of Geodesy and Geophysics in Grenoble in August 1975.

The Special Committee for Solar Terrestrial Physics of the International Council of Scientific Unions has established a working group on Solar-Terrestrial Physics and Meteorology. A publication "Solar-Terrestrial Physics and Meteorology: A Working Document" including a selected bibliography, an address list of recent authors, selected key dates and data, and selected contemporary reviews is available from the Special Committee for Solar-Terrestrial Physics, c/o National Academy of Sciences, 2101 Constitution Avenue, Washington, D.C. 20418. A joint USA/USSR Working Group on Influence of Solar Activity on Climate has held several meetings in the U.S.A. and U.S.S.R. The National Aeronautics and Space Administration has established an Advisory Committee on Sun-Weather Investigations.

IV. Recommendations

Since the view of an inter-disciplinary committee may carry greater weight than the view of an individual, this section is excerpted from the Report (Sturrock et al., 1976) of a Committee* to advise NASA Headquarters on the Relationship Between Solar Activity and Terrestrial Weather:

1. We have studied the literature and we conclude that there is a *prima facie* case for influence of the sun on terrestrial weather on a time scale of a few days.

2. We advocate a careful and extended statistical study of selected indicators of solar and terrestrial phenomena with a view of (a) confirming or disproving the present apparent relationship; (b) determining the reality or otherwise of proposed 11-year and 22-year associations; and (c) searching for a causal chain responsible for any such association.

3. We advocate a program of theoretical research with a view to searching for possible causal chains between the sun and the earth's lower atmosphere and examining proposals in terms of physical processes and meteorological models.

Concerning recommendation 2(a) above, we suggest that there be a study of the morphology of the apparent influence of the solar and interplanetary sector structure on the vorticity area index, tropospheric variations, the zonal index and other meteorological variables. In addition, high priority should be given to completely new studies (hopefully involving different variables and different methods of analysis and possibly different scientists) which may either confirm or negate the results of recent studies.

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* The composition of the Committee is as follows: Guenter E. Brueckner, Naval Research Laboratory; Robert E. Dickinson, National Center for Atmospheric Research; Norihiko Fukuta, University of Denver; Louis J. Lanzerotti, Bell Laboratories; Richard S. Lindzen, Harvard University; Chung G. Park, Stanford University; Peter A. Sturrock, Stanford University, Chairman; and John M. Wilcox, Stanford University.

Concerning item 2(c) above, the Committee recommends searching for correlations between pairs of variables listed in Table 1, as exemplified by the questions listed in Table 2. Some of the questions listed in Table 2 are susceptible also to theoretical analysis and to model analysis, and are therefore specific examples of the general point made in recommendation 3 above.

TABLE 1

VARIABLES POSSIBLY RELEVANT TO CAUSAL CHAIN RELATING THE SUN TO TERRESTRIAL WEATHER

SUN	INTERPLANETARY MEDIUM	MAGNETOSPHERE	IONOSPHERE	GROUND LEVEL
ROTATION	SOLAR WIND SPEED, DENSITY, TEMPERATURE, COMPOSITION	TRAPPED PARTICLE DISTRIBUTIONS	SIZE OF AURORAL ELECTROJET (A_e INDEX)	RAINFALL
SUNSPOT NUMBER	MAGNETIC FIELDS		$n_e(h)$	WINDS, GROUND WINDS 500 mb
FLARE ACTIVITY	PARTICLE FLUX (SOLAR, GALACTIC)		TOTAL ELECTRON CONTENT	PRESSURE
LARGE SCALE MAGNETIC FIELDS				THUNDERSTORMS (GLOBAL)
10 cm RADIO EMISSION				ELECTRIC FIELDS
				MAGNETIC FIELDS
				CLOUD COVER
				OZONE CONTENT
				TREE RING HISTORY

TABLE 2

OUTSTANDING QUESTIONS

A PRIORITY

1. RELATION OF IONOSPHERIC AND GROUND-LEVEL ELECTRIC FIELDS (D, T)
2. IONIZATION OF STRATOSPHERE BY GALACTIC COSMIC RAYS (D, T)
3. CHANGE OF CONDUCTIVITY OF ATMOSPHERE BY COSMIC RAY FLUX (D, T)
4. EFFECT OF ULTRAVIOLET AND CHARGED-PARTICLE FLUXES ON OZONE AND NITRIC OXIDE (D, M)
5. EFFECT OF OZONE AND NITRIC OXIDE ON CLIMATE MODELS (T, M)
6. EFFECT OF FAIR-WEATHER ELECTRIC FIELDS ON THUNDERSTORMS AND PRECIPITATION (D, T)

B PRIORITY

7. EFFECT OF SECTOR MAGNETIC FIELD ON SOLAR PARTICLE FLUX (D, T)
8. EFFECT OF STRATOSPHERIC IONIZATION ON FORMATION OF CONDENSATION NUCLEI (D, T)
9. CRITERIA FOR RAINFALL AND INFLUENCE ON METEOROLOGICAL MODELS (T, M)
10. MODULATION OF GALACTIC COSMIC RAYS BY SOLAR MAGNETIC FIELDS (D, T)
11. SOLAR WIND VELOCITY AND DENSITY AS A FUNCTION OF SECTOR STRUCTURE (D, T)
12. COUPLING OF SOLAR MAGNETIC FIELDS TO MAGNETOSPHERE (D, T)
13. CHARGE GENERATION IN THUNDERSTORMS (T)

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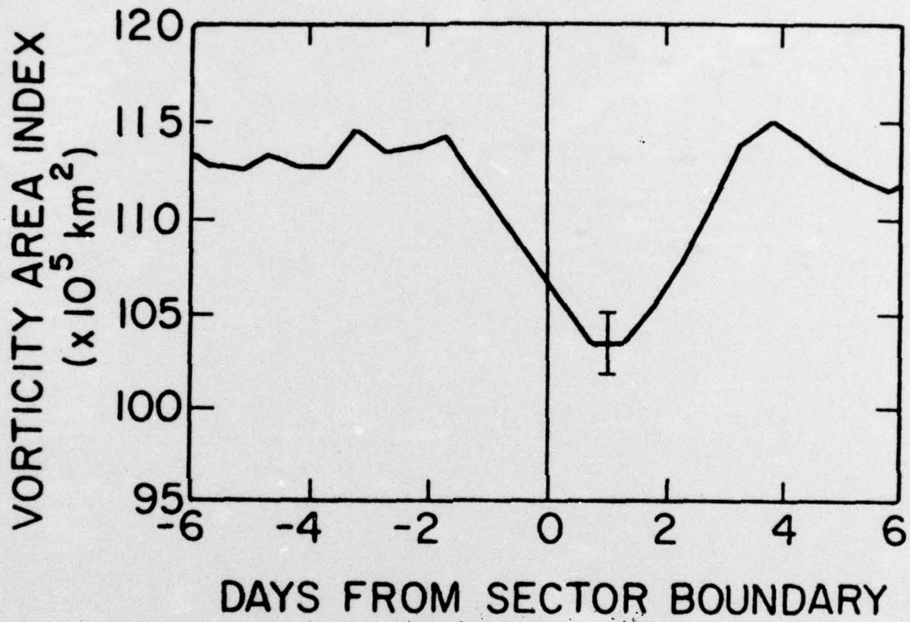
Figure 1

Average response of the vorticity area index (the area of all the low pressure troughs in the northern hemisphere) about times when solar magnetic sector boundaries were carried past the earth by the solar wind. Sector boundaries were carried past the earth by the solar wind on day 0. The analysis includes 54 boundaries during the winter months November to March in the years 1964 to 1970. The standard error of the mean (error bar) was calculated after subtracting a 27-day mean centered on each sector boundary, to remove long-term trends. The deviations corresponding to the individual boundaries are consistent with a normal distribution about the mean.

Figure 2

Same format as Figure 1; the list of boundaries used in Figure 1 was divided into two parts according to (a) the magnetic polarity change at the boundary, (b) the first or last half of the winter, and (c) the yearly intervals 1964 to 1966 and 1967 to 1970. (a) The dotted curve represents 24 boundaries in which the interplanetary magnetic field polarity changed from toward the sun to away and the dashed curve 29 boundaries in which the polarity changed from away to toward. (b) The dotted curve represents 31 boundaries in the interval 1 November to 15 January, and the dashed curve 22 boundaries in the interval 16 January to 31 March. (c) The dotted curve represents 26 boundaries in the interval 1964 to 1966, and the dashed curve 27 boundaries in the interval 1967 to 1970. The curves have been arbitrarily displaced in the vertical direction, but the scale of the ordinate is the same as in Figure 1; that is, each interval is $5 \times 10^5 km^2$.

Figure 3 — Same format as Figure 1; for (a) 50 of the boundaries used in the original work, and (b) 81 new boundary passages not included in the original analysis.



VORTICITY AREA INDEX
(x 10^5 km^2)
120
115
110
105
100
95
-6
-4
-2
0
2
4
6
DAYS FROM SECTOR BOUNDARY

Figure 1

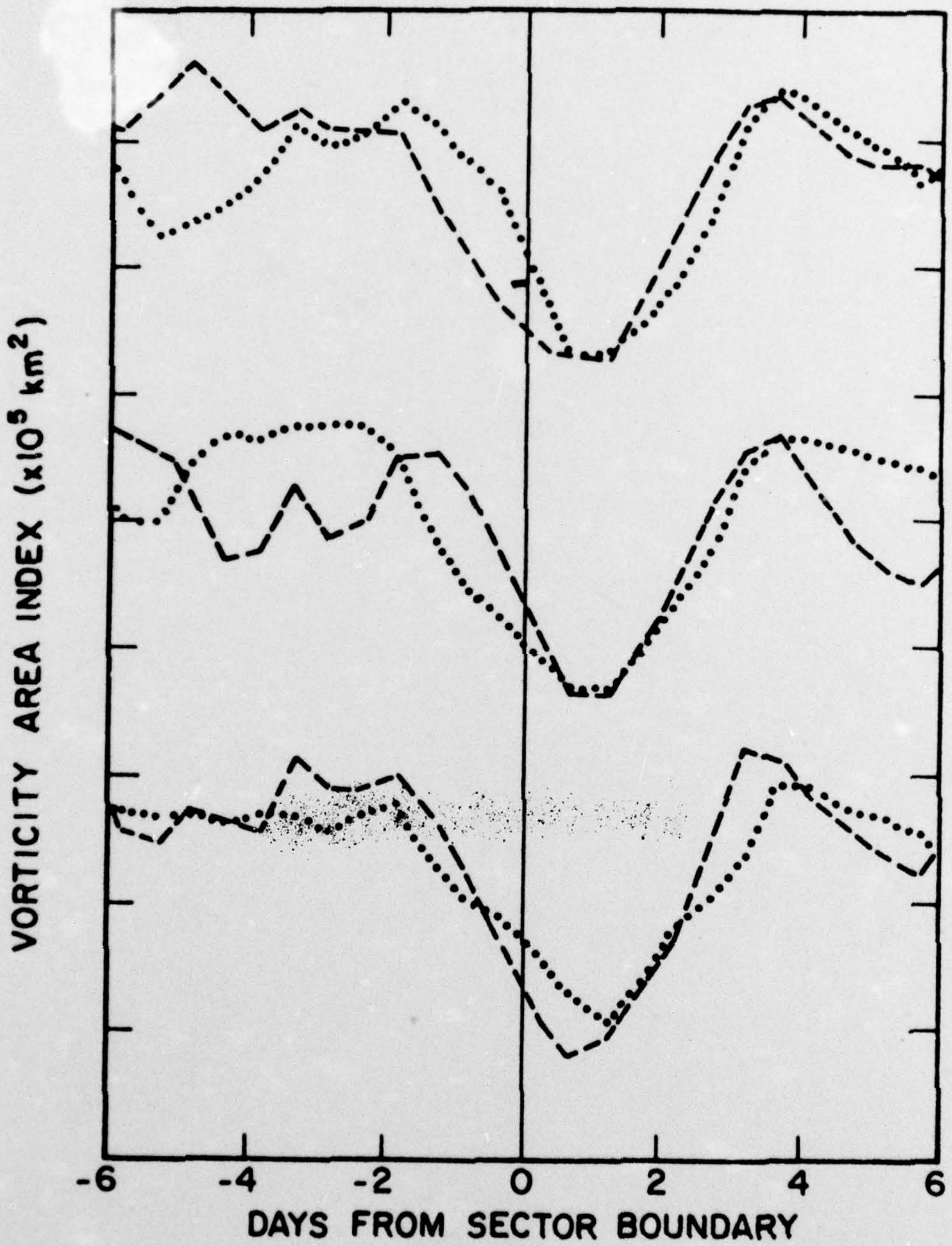
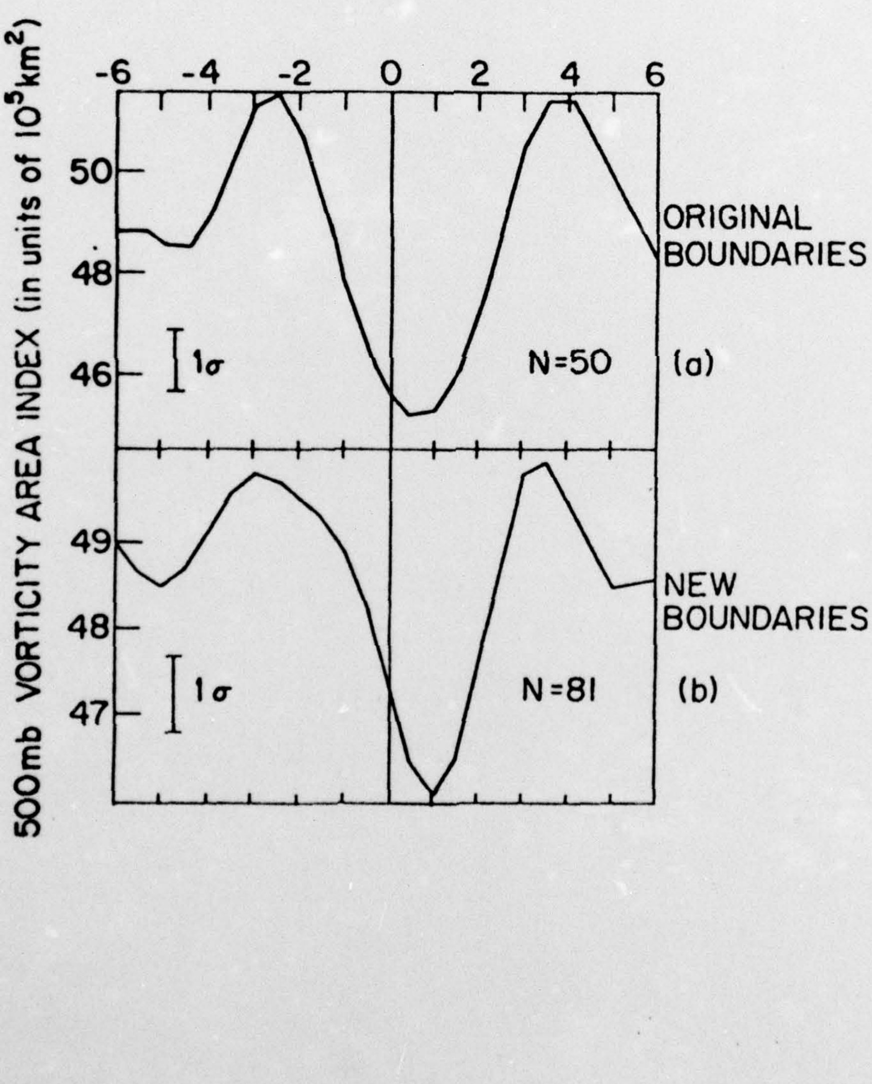

VORTICITY AREA INDEX (x10^5 km^2)
-6
-4
-2
0
2
4
6
DAYS FROM SECTOR BOUNDARY

Figure 2



500mb VORTICITY AREA INDEX (in units of 10^5 km^2)
-6
-4
-2
0
2
4
6
50
48
46
1σ
N=50
ORIGINAL
BOUNDARIES
(a)
49
48
47
1σ
N=81
NEW
BOUNDARIES
(b)

Figure 3